Outline

- Relativistic Kinematics
  - (4-momentum)2 invariance, invariant mass
  - Hypothesis testing, production thresholds
  - Cross-sections, flux and luminosity, accelerators
  - Particle lifetime, decay length, width
- Classification of particles
  - Fermions and bosons
  - Leptons, hadrons, quarks
  - Mesons, baryons
- Quark Model
  - Meson and baryon multiplets
  - Isospin, strangeness, c, b, t quarks
- Particle Interactions
  - Colour charge, QCD, gluons, fragmentation, running couplings
  - Strong and weak decays, conservation rules
  - Virtual particles and range of forces
  - Parity, charge conjugation, CP
  - Weak decays of quarks
  - Charmonium and upsilon systems
- Electroweak Interactions
  - Charged and neutral currents
  - W, Z, LEP experiments
  - Higgs and the future
- LHC Experiments
- Future – introduction to accelerator phy

Today

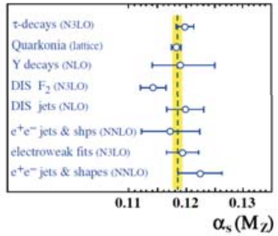
Lecture 12 (4 slides/page) - Particle decays, strong and weak decays, conservation rules
- Griffiths, pp. 66-71,79-82, 84-85.

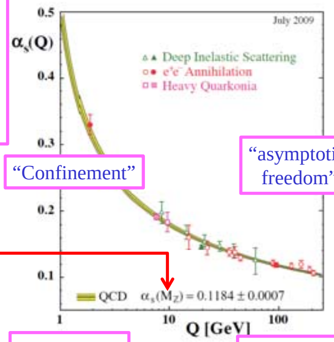
Previous lecture

Lecture 11 (4 slides/page) - Fragmentation, running couplings
- Halzen and Martin,pp. 16-26
- Griffiths, pp. 298-301
- Williams, pp. 221-227
- Perkins (3rd edition), pp. 44-46
- Griffiths, pp. 283-288
- Martin, pp. 160-164.

α_s Summary

Consistent value of α_s measured in many different reactions. Note that values are all transformed ("evolved") to a single energy scale to allow comparison, using "Renormalisation Group Equations". QCD predicts how α_s varies with energy, not its actual value





"Confinement"

"asymptotic freedom"

Long range (low energy)

Short range (high energy)

K. Nakamura *et al.* (Particle Data Group), J. Phys. G 37, 075021 (2010) [http://pdg.lbl.gov/2011/reviews/rpp2011-rev-qcd.pdf]

[For info.] Running Couplings

EM case

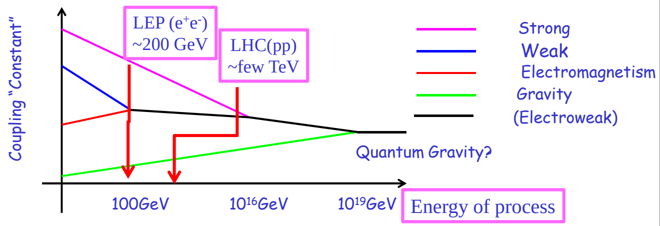
$$\alpha_{EM}\left(\left|q^2\right|\right) = \frac{\alpha(0)}{1-\left(\frac{\alpha(0)}{3\pi}\right)\ln\left(\left|q^2\right|/m^2\right)} \qquad \left|q^2\right| >> m^2$$

QCD case

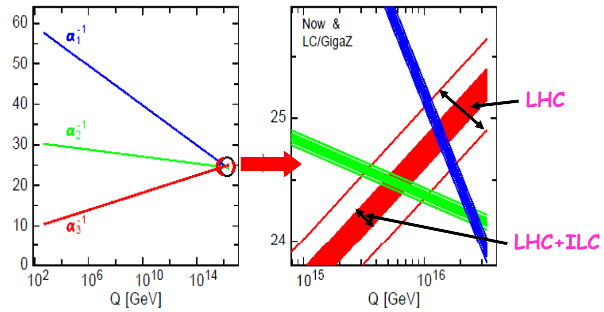
$$\alpha_S\left(\left|q^2\right|\right) = \frac{\alpha_S(\mu^2)}{1+\left(\frac{\alpha_S(\mu^2)}{12\pi}\right)\left[11N_{colours}-2N_{flavours}\right]\ln\left(\left|q^2\right|/m^2\right)} \qquad \left|q^2\right| >> \left|\mu^2\right|$$

Unification of Forces

- Coupling "constants" are said to "run" (change their strength) with energy
- For electromagnetism, the coupling "constant", α_{EM}, increased with energy
- For weak force the coupling constant decreases with energy
  - E.M. and weak merge at ~100 GeV: "electroweak unification"
- For strong force coupling, α_s, decreases with energy



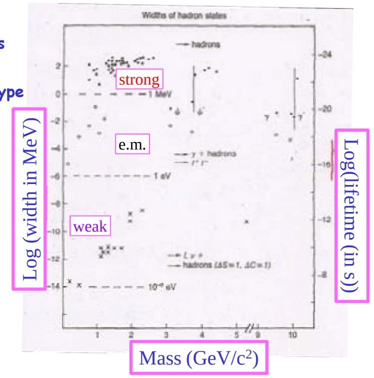
Requires gauge coupling unification
Low energy SUSY
Nucleon decay



[Allanach, Blair, Kraml, Martyn, Polesello, Porod,Zerwas, LHC-LC Report, p339]

Strong, e.m., weak interactions (W.I.)

- So far, have discussed strong interaction in terms of binding quarks into hadrons
- Particle decays also determined by type of interactions allowed
- Strength of interaction reflected in lifetime of decaying particle
- Many hadronic resonances, lifetimes
  - $\tau \sim 10^{-23}$s
  - Deduced from width, $\Gamma \sim 10\text{-}100$ MeV
  - These are Strong Interaction decays
- Some much longer lived hadrons
  - $\tau \sim 10^{-10}$s
  - Can be measured directly
  - These are Weak Interaction decays
- Some with intermediate lifetimes (e.m.)



Conservation Rules

Interaction	Symbol	SI	EM	WI
Energy	E	✓	✓	✓
Momentum	P	✓	✓	✓
Angular Mom$^{n.}$	J	✓	✓	✓
Charge (e.m, colour)	Q	✓	✓	✓
Fermion number		✓	✓	✓
Quark number		✓	✓	✓
Baryon number	B	✓	✓	✓
Lepton number	L	✓	✓	✓
Electron number	L_e	✓	✓	✓
Muon number	L_m	✓	✓	✓
Tau number	L_t	✓	✓	✓
Quark flavour		✓	✓	×
Isospin	I	✓	×	×
Parity	P	✓	✓	×
Charge Conjugtion	C	✓	✓	×
Time reversal	T	✓	✓	×
Matter-Antimatter	CP	✓	✓	×
Quantum Field Theory	CPT	✓	✓	✓

✓ conserved
× Not necessarily conserved